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Impacts of high temperature on adverse birth outcomes in Seoul, Korea: Disparities by individual- and community-level characteristics

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ABSTRACT

Background: Few studies have examined temperature's effect on adverse birth outcomes and relevant effect modifiers.

Objectives: We investigated associations between heat and adverse birth outcomes and how individual and community characteristics affect these associations for Seoul, Korea, 2004–2012.

Methods: We applied logistic regression to estimate associations between heat index during pregnancy, 4 weeks before delivery, and 1 week before delivery and risk of preterm birth and term low birth weight. We investigated effect modification by individual (infant's sex, mother's age, and mother's educational level) and community characteristics (socioeconomic status (SES) and percentage of green areas near residence at the gu level, which is similar to borough in Western countries). We also evaluated associations by combinations of individual- and community-level SES.

Results: Heat exposure during whole pregnancy was significantly associated with risk of preterm birth. An interquartile (IQR) increase (5.5 °C) in heat index during whole pregnancy was associated with an odds ratio (OR) of 1.033 (95% CI 1.005, 1.061) with NO_2 adjustment, and 1.028 (95% CI 0.998, 1.059) with PM_{10} adjustment, for preterm birth. We also found significant associations with heat exposure during 4 weeks before delivery and 1 week before delivery on preterm birth. We did not observe significant associations with term low birth weight. Higher risk of heat on preterm birth was associated with some individual characteristics such as infants with younger or older mothers and lower community-level SES. For combinations of individual- and community-level SES, the highest and most significant estimated effect was found for infants with low educated mothers living in low SES communities, with suggestions of effects of both individual-and community-level SES.

Conclusions: Our findings have implications for evaluating impacts of high temperatures on birth outcomes, estimating health impacts of climate change, and identifying which subpopulations and factors are most relevant for disparities in this association.

1. Introduction

Although many studies have reported adverse health impacts of high temperature on adults and the elderly, relatively few studies have evaluated the effect of temperature on maternal and child health, which are critical public health concerns. Adverse birth outcomes can contribute to the burden of disease on future growth and development. Preterm birth (PTB), defined as the birth of an infant prior to 37 weeks' gestation, has been associated with several adverse health outcomes such as morbidity, mortality and lifelong impacts in cognitive functioning and behavior (Harding and Maritz, 2012; Petrou et al., 2003). Low birth weight (LBW), defined as births less than 2500 g, is also a major determinant of mortality and morbidity in fetus, infants, and children (Rashid et al., 2017; Harding and Maritz, 2012).

Recently, an increasing number of studies of ambient temperature have reported associations with several adverse birth outcomes such as preterm birth, low birth weight, and stillbirth (Basu et al., 2017; Ha et al., 2017a, 2017b; Strand et al., 2012; Zhang et al., 2017). Auger et al. (2014) reported that high ambient temperature and extreme heat episodes may trigger earlier delivery among term births. Basu et al. (2010) found that high ambient temperature was significantly associated with preterm birth. Another study observed that air temperature during pregnancy was associated with lower birth weight and shorter gestational age (Kloog et al., 2015). Given that climate change is

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anticipated to result in an overall warming with more temperature extremes, scientific evidence is needed on the impacts of heat exposure on adverse birth outcomes.

Several studies demonstrated that individual- or community-level factors may affect the association of heat-related adverse birth outcomes. Younger or older maternal age, low education, maternal race, and lower socioeconomic status (SES) are generally associated with the association between temperature and risk of adverse birth outcomes (Zhang et al., 2017). Community characteristics such as mother's residential greenness, population density, and area-level SES may modify the risk. However, despite the increasing number of studies on the association between temperature and adverse birth outcomes, scientific evidence of potential effect modifiers on this association in various locations is still insufficient. Understanding which populations are vulnerable and which factors are most relevant to disparities in associations would benefit the development of more targeted and effective intervention strategies.

To the best of our knowledge, no study has investigated the associations between heat exposure based on various exposure windows and adverse birth outcomes or effect modification by several individual- and community-level characteristics on heat-related adverse birth outcomes for Korea. Our findings conducted in a different area and time frame from other studies adds evidence to the relatively limited and inconsistent body of literature regarding the association between heat exposure and adverse birth outcomes. In addition, our study considered multiple exposure windows for heat exposure on adverse birth outcomes. We investigated associations between heat exposure and adverse birth outcomes (preterm birth and term low birth weight) using birth data in Seoul, Korea, 2004–2012. We estimated risks for whole pregnancy, 4 weeks before delivery, and 1 week before delivery. We also investigated how individual and community characteristics affect these associations. Further we considered combinations of individual- and community-level SES, as both can play a role in health.

2. Methods

2.1. Data

We obtained birth certificate data for 2004–2012 from the Korean National Statistical Office for Seoul, Korea. Data included residential address at birth, infant's sex, birth weight, gestational age, birth order, birth date, mother's age, and mother's education. We excluded subjects with incomplete data for covariates for infant's sex, gestational age, birth weight, or maternal characteristics (i.e., mother's age or education). We restricted study subjects to singleton births. The study included 813,820 births. We considered two birth outcomes: (1) preterm birth defined as gestational age $<$ 37 weeks; and (2) term low birth weight defined as gestational age $\geq$ 37 weeks and birth weight less than 2500 g. Mother's age was categorized as $<$ 25, 25–29, 30–34, and $\geq$ 35 years. Educational level of mother was categorized as $\leq$ 12 and $>$ 12 years.

Hourly measurements of ambient temperature and relative humidity for Seoul were obtained from the National Meteorological Administration, Republic of Korea. Seoul has one central monitoring site for meteorological data. We calculated 24-hr average values for temperature and humidity. We then calculated heat index, which is a function of air temperature and relative humidity, as the exposure index. We used a heat index algorithm by the U.S. National Weather Service (NWS) (NWS, 2016). We considered multiple exposure windows for heat index for each study subject for: (1) gestational exposure from conception to birth; (2) 4 weeks before delivery; and (3) 1 week before delivery.

We obtained community-level characteristics data at the gu level from Seoul Statistics, Seoul Metropolitan Government (Seoul Statistics, 2018). Seoul has 25 gus. A gu is an administrative unit in South Korea, which is similar to a borough in Western countries. To examine community-level effect modification, we considered community-level SES and residential greenness. Community-level SES was based on Seoul Statistics data for local taxes including income tax, automobiles tax, and property tax of each gu level. Residential greenness was based on Seoul Statistics data for total areas of green spaces including facilities green space, park, forest, waterside road green spaces of each gu level for each study subject's residence.

To perform analysis with adjustment for air pollution exposure, we obtained hourly concentrations of PM_{10}, NO_2, and O_3 for each gu for the study period from the Department of Environment, Republic of Korea. $PM_{2.5}$ data were not available. For each gu, we calculated daily values (24-h averages) for PM_{10}, NO_2, and O_3. Like our study, several studies used 24-h average for the ozone metric (Salam et al., 2005; Liu et al., 2003) and reported high correlations among 3 metrics (24-h average, daily 8-h maximum, and daily 1-h maximum) (Li et al., 2015). We considered exposures for the gestation period, 4 weeks before delivery, and 1 week before delivery, matching the exposure timeframes for heat index.

2.2. Statistical analysis

We applied logistic regression to estimate the association between heat exposure and adverse birth outcomes (preterm birth and term low birth weight). Models estimated the odds ratio (OR) of the presence of the preterm (yes/no) or term low birth weight (yes/no) for an interquartile range (IQR) increase (5.5 °C) in heat index during pregnancy, 4 weeks before delivery, or 1 week before delivery. Models were adjusted for infant's sex, mother's age, mother's educational level, year and month of birth, and air pollution level. We conducted analysis of each birth outcome and exposure window separately. Analysis for 1 week before delivery was not considered for term low birth weight due to biological plausibility. For adjustment by air pollution, each pollutant was fitted in a separate model, and a model was fitted without adjustment by pollution. The exposure window of air pollution was matched to that of the heat exposure. To examine the effect modification of individual-level characteristics (i.e., infant's sex, mother's age, and mother's educational level) and community-level characteristics (i.e., community-level SES and residential greenness), stratified analyses were conducted for each variable. We reported statistical difference by calculating the difference between the two estimates and 95% confidence interval for the difference by each comparison group of characteristics. For the community characteristics variables, we divided births into a low group for gu's with values $<$ median of the distribution and a high group for gu's with values $\geq$ median of the distribution of the gus. We also evaluated associations by combinations of individual- and community-level SES.

We added sensitivity analysis for study period based on date of conception. Our study period was from 2004 to 2012. Thus, we excluded births with an estimated date of conception before August 7, 2003 or after February 19, 2014 (i.e., restricting the conception date range to 21 weeks (shortest pregnancy) before start day and 45 weeks (longest pregnancy) before the end day) to avoid the fixed cohort bias. We also conducted additional analysis using extended Cox proportional hazard model with time-dependent covariates as an alternative approach.

Analyses were conducted using SAS (version 9.2; SAS Institute Inc., Cary, NC, USA). Results were expressed as the OR per IQR increment of heat index during pregnancy.

3. Results

Table 1 shows characteristics of the study population. Of the 813,820 study subjects, 4.0% were preterm births and of the 780,912 term births, term low birth weight occurred in 1.6%. Preterm birth rate (4.0%) in our study is similar to those in other studies (Zheng et al., 2018; Schifano et al., 2016; Vicedo-Cabrera et al., 2015). The study

Table 1
Characteristics of the study population in Seoul, Korea, 2004–2012.

	Entire cohort	Preterm birth (< 37 weeks)	Term births	Term low birth weight (< 2500 g)
Study population [n (%)]	813,820	32,908 (4.0)	780,912 (96.0)	12,298 (1.6)
Covariates [n (%)]				
Sex				
Male	418,863 (51.5)	18,471 (56.1)	400,392 (51.3)	4887 (39.7)
Female	394,957 (48.5)	14,437 (43.9)	380,520 (48.7)	7411 (60.3)
Mother's age (years)				
< 25	31,544 (3.9)	1288 (3.9)	30,256 (3.9)	640 (5.2)
25–29	254,216 (31.2)	8901 (27.0)	245,315 (31.4)	3635 (29.6)
30–34	394,723 (48.5)	15,376 (46.7)	379,347 (48.6)	5698 (46.3)
≥ 35	132,580 (16.3)	7293 (22.2)	125,287 (16.0)	2308 (18.8)
Unknown	757 (0.1)	50 (0.2)	707 (0.1)	17 (0.1)
Educational level of mother (years)				
≤ 12	227,736 (28.0)	10,699 (32.5)	217,037 (27.8)	3963 (32.2)
> 12	583,662 (71.7)	22,046 (67.0)	561,616 (71.9)	8276 (67.3)
Unknown	2422 (0.3)	163 (0.5)	2259 (0.3)	59 (0.5)
Year of birth				
2004	95,579 (11.7)	3538 (10.8)	92,041 (11.8)	1317 (10.7)
2005	86,393 (10.6)	3281 (10.0)	83,112 (10.6)	1201 (9.8)
2006	89,343 (11.0)	3480 (10.6)	85,863 (11.0)	1321 (10.7)
2007	96,382 (11.8)	3707 (11.3)	92,675 (11.9)	1431 (11.6)
2008	91,202 (11.2)	3761 (11.4)	87,441 (11.2)	1455 (11.8)
2009	86,368 (10.6)	3552 (10.8)	82,816 (10.6)	1314 (10.7)
2010	89,976 (11.1)	3781 (11.5)	86,195 (11.0)	1345 (10.9)
2011	88,308 (10.9)	3742 (11.4)	84,566 (10.8)	1430 (11.6)
2012	90,269 (11.1)	4066 (12.4)	86,203 (11.0)	1484 (12.1)
Month of birth				
January	78,017 (9.6)	3186 (9.7)	74,831 (9.6)	1109 (9.0)
February	66,674 (8.2)	2572 (7.8)	64,102 (8.2)	971 (7.9)
March	73,554 (9.0)	2833 (8.6)	70,721 (9.1)	1105 (9.0)
April	68,143 (8.4)	2624 (8.0)	65,519 (8.4)	1064 (8.7)
May	65,847 (8.1)	2561 (7.8)	63,286 (8.1)	934 (7.6)
June	62,315 (7.7)	2648 (8.1)	59,667 (7.6)	950 (7.7)
July	64,776 (8.0)	2854 (8.7)	61,922 (7.9)	1010 (8.2)
August	67,327 (8.3)	2918 (8.9)	64,409 (8.3)	1019 (8.3)
September	69,468 (8.5)	2770 (8.4)	66,698 (8.5)	1095 (8.9)
October	70,978 (8.7)	2740 (8.3)	68,238 (8.7)	1098 (8.9)
November	66,332 (8.2)	2633 (8.0)	63,699 (8.2)	1036 (8.4)
December	60,389 (7.4)	2569 (7.8)	57,820 (7.4)	907 (7.4)

Table 2
ORs (95% CI) for preterm birth and term low birth weight for an IQR increase (5.5 °C) in heat index during pregnancy, 4 weeks before delivery, and 1 week before delivery with and without air pollution adjustment.

	OR (95% CI)	
	Preterm birth	Term low birth weight
NO_2 adjustment		
Whole pregnancy	1.033 (1.005, 1.061)	1.006 (0.961, 1.052)
4 weeks before delivery	1.013 (1.005, 1.022)	1.005 (0.990, 1.019)
1 week before delivery	1.012 (1.004, 1.020)	-[a]
PM_{10} adjustment		
Whole pregnancy	1.028 (0.998, 1.059)	1.002 (0.954, 1.053)
4 weeks before delivery	1.019 (1.010, 1.029)	1.007 (0.991, 1.023)
1 week before delivery	1.018 (1.009, 1.027)	-[a]
O_3 adjustment		
Whole pregnancy	1.013 (0.985, 1.041)	0.988 (0.943, 1.036)
4 weeks before delivery	1.008 (0.999, 1.017)	1.010 (0.995, 1.024)
1 week before delivery	1.009 (1.001, 1.017)	-[a]
No adjustment for pollution variables		
Whole pregnancy	0.989 (0.969, 1.010)	0.990 (0.957, 1.024)
4 weeks before delivery	1.010 (1.003, 1.017)	1.007 (0.996, 1.018)
1 week before delivery	1.009 (1.003, 1.015)	-[a]

Note: Models were adjusted for infant's sex, mother's age, mother's education level, birth year, and birth month.
[a] For term low birth weight, exposure for 1 week before delivery were not estimated due to biological plausibility.

population had more males than females (51.5% vs. 48.5%). The most frequent mother's age categories were 25–29 years (31.3%) and 30–34 years (48.6%). Most infants had mothers in the most educated group of > 12 years (71.9%). The distribution of population characteristics for those with preterm birth or term low birth weight showed similar patterns with a higher percentage of mothers ages 25–29 years or 30–34 years, and a higher percentage of high educated mothers, except for infant's sex for which there was a higher percentage of females for term low birth weight infants. The percentage of infants by year of birth and month of birth were similar across the total population and those with

adverse birth outcomes (preterm birth and term low birth weight). Table S1 provide summary statistics of heat index based on various exposure windows. Heat index level by birth outcomes showed similar patterns compared with those of total population for whole pregnancy. For 4 weeks before delivery or 1 week before delivery, heat index level for those with adverse birth outcomes was slightly higher with for those of the total population. Distribution of birth weight of the study subjects is provided in Table S2.

As a preliminary analysis, we investigated the relationship between adverse birth outcomes and covariates from a model without a heat index variable (Table S3). Risk of preterm birth was higher in male infants, while female infants were 1.595 (95% confidence interval (CI): 1.522, 1.672) times more likely to have term low birth weight than male infants. Infants with younger (< 25 years) or older (30–34 or ≥ 35 years) mothers had higher risk for both preterm birth and term low birth weight than those with mothers age 25–29 years. Risks of both birth outcomes were higher in infants with less educated mother (≤ 12 years).

Table S4 shows correlations of heat index and air pollution levels during whole pregnancy. Heat index during whole pregnancy and air pollution levels were not highly correlated with each other ($r = -0.32$ for PM_{10}; $r = -0.23$ for NO_2; $r = 0.36$ for O_3).

Table 2 shows odds ratios for adverse birth outcomes during various exposure windows for heat index with and without adjustment for air pollution. All models were adjusted by infant's sex, mother's age, mother's education level, birth year, and birth month. We observed significant positive associations between all exposure windows for heat and preterm birth. An IQR increase (5.5 °C) in heat index during whole pregnancy was associated with an OR of 1.033 (95% CI 1.005, 1.061) with adjustment for NO_2, and 1.028 (95% CI 0.998, 1.059) with adjustment for PM_{10} for preterm birth. We also found significant associations with heat exposure during 4 weeks before delivery and 1 week before delivery on preterm birth. We did not find statistically significant associations with term low birth weight.

For exposure timeframe and birth outcome for which we observed the largest and significant associations (i.e., whole pregnancy for preterm birth), we assessed the effect modification by individual and community characteristics (Table 3). Associations between heat exposure during whole pregnancy and preterm birth were higher in females than males although these results were not statistically different. We found significantly higher risk in infants with younger or older mothers compared to mothers age 25–29 years. The risk was the highest in infants with youngest mothers. On the other hand, we found lower risk of heat index and preterm birth for infants with mothers age 25–29 years, however results were not statistically significant. Infants with low educated mothers had slightly higher risk of heat index and preterm birth, although the result was not statistically different. For the community characteristics, we assigned gus into two groups: low as < median of the distribution and high as ≥ median of the distribution of gus. Higher risks of heat index during pregnancy on preterm birth were associated with lower community-level SES, although the result was not statistically different. For residential greenness, we found similar effects for the low and high greenness groups.

We conducted additional analysis to assess combined disparities in the heat and preterm birth association by combinations of individual- and community-level SES (Table 4). Individual-level SES was based on mother's educational level. For combinations of individual- and community-level SES, the highest and most significant association was found in infants with low educated mothers living in lower community-level SES. Of lower educated mothers, the risk of heat exposure on preterm birth in infants was only observed for those living in low community-level SES, indicating that community-level SES also plays a role.

To avoid fixed cohort bias, we added sensitivity analysis for study period based on date of conception (Table S5). Effect estimates were similar to those of the original findings. As an alternative statistical approach, we performed extended Cox proportional hazard model for the risk of preterm birth (Table S6). Hazard ratios for sensitivity analysis were similar with original findings.

Table 3
ORs (95% CI) for preterm birth for an IQR increase (5.5 °C) in average heat index during whole pregnancy, stratified by several individual-level and community-level characteristics.

Characteristics	N (%)	Preterm birth
Individual characteristics		
Sex		
Male	418,863 (51.5)	1.026 (0.990, 1.063)
Female	394,957 (48.5)	1.041 (0.999, 1.084)
Mother's age (years)		
< 25	31,544 (3.9)	1.187 (1.031, 1.367)[c]
25–29	254,216 (31.3)	0.969 (0.919, 1.022)[c]
30–34	394,723 (48.6)	1.046 (1.006, 1.088)[c]
≥ 35	132,580 (16.3)	1.049 (0.993, 1.109)[c]
Educational level of mother (years)		
≤12	227,736 (28.1)	1.046 (0.997, 1.098)
> 12	583,662 (71.9)	1.026 (0.993, 1.059)
Community characteristics		
SES[a]		
Low	415,213 (51.0)	1.049 (1.009, 1.089)
High	398,607 (49.0)	1.016 (0.978, 1.055)
Residential greenness[b]		
Low	408,392 (50.2)	1.034 (0.995, 1.075)
High	405,428 (49.8)	1.031 (0.993, 1.070)

Note: Models were adjusted for infant's sex, mother's age, mother's education level, NO_2 level, birth year, and birth month; For community characteristics, a low group was defined as those with values < median of the distribution and a high group as those with values ≥ median of the distribution of the gus. Below are the comparisons of the OR that were statistically significant:
[c] Preterm birth OR were 1.22 (1.05, 1.43), 1.08 (1.01, 1.15), and 1.08 (1.00, 1.17) times higher for < 25, 30-34, and ≥35 than 25-29 years, respectively.
[a] Community-level SES was based on local taxes including income tax, automobiles tax, property tax of each gu level.
[b] Residential greenness was based on percentage of green areas at each gu level.

Table 4
ORs (95% CI) for preterm birth for an IQR increase (5.5 °C) in heat index during whole pregnancy, stratified by combinations of individual- and community-level SES.

Community-level SES[a]	Individual-level SES[b]	
	Low	High
Low	1.100 (1.032, 1.173)	1.019 (0.972, 1.069)
High	0.973 (0.904, 1.048)	1.031 (0.986, 1.077)

[a] Community-level SES was based on local taxes including income tax, automobiles tax, and property tax of each gu level.
[b] Individual-level SES was based on mother's education level.

4. Discussion

In this study, we found that heat exposure during the whole pregnancy, 4 weeks before delivery, and 1 week before delivery was significantly associated with increased risk of preterm birth. Higher risk of heat on preterm birth was associated with some individual characteristics such as infants with younger or older mothers and those living in gus with lower community-level SES. For combined disparities in the heat and preterm birth association, the highest and most significant impact was found in infants with low educated mothers living in gus with lower community-level SES.

Consistent with our findings, previous studies reported that gestational exposure to heat is associated with several adverse birth outcomes including preterm birth (Auger et al., 2014; Cox et al., 2016;

Poursafa et al., 2015; Schifano et al., 2016; Strand et al., 2012; Zhang et al., 2017). In this study we found significant associations for preterm birth for heat index during whole pregnancy, 4 weeks before delivery, and 1 week before delivery for preterm birth. Many previous studies investigating the effect of temperature on preterm birth have identified particular periods of susceptibility to temperature during whole pregnancy, during the last month, last week or days before birth. Consistent with our findings, recent studies found associations of preterm birth with long-term exposure to temperature during the entire pregnancy (Zheng et al., 2018; He et al., 2016). Basu et al. (2017) investigated the relationship between apparent temperature and preterm delivery and found that increased average cumulative weekly apparent temperature is associated with higher risk of preterm delivery. Another U.S. study found that acute (e.g., during weeks 1–7, during the week preceding delivery) and chronic (e.g., whole pregnancy) heat exposures increased risk for early preterm and early term delivery (Ha et al., 2017a). In this study, we did not find significant associations between heat index and term low birth weight. Relatively few studies explored low birth weight in relation to heat and the results were inconsistent. A U.S. study reported that heat exposure during the third trimester and whole pregnancy increased risk of term low birth weight (Ha et al., 2017b). Consistent with our findings, other studies demonstrated no effect of ambient temperature on low birth weight (Wolf and Armstrong, 2012; Diaz et al., 2016). Rashid et al. (2017) found that higher temperature at mid-gestation was associated with increased birth weight. Some studies reported that low temperatures rather than high temperatures are more associated with decreased birth weight (Poursafa et al., 2015; Zhang et al., 2017).

The biologic mechanism for adverse birth outcomes with heat exposure is not well understood. Pregnant women may be more susceptible to temperature change. Possible explanations include decreased uterine activity and blood flow, increased dehydration, inadequate thermoregulation, increased prenatal inflammation, increased blood viscosity, elevated cholesterol levels, and a higher sweating threshold with high temperatures could contribute to pregnant women and developing fetus and promote preterm delivery or adverse birth outcomes (Khamis et al., 1983; Stan et al., 2013).

Individual and maternal characteristics and behaviors may increase susceptibilities to adverse birth outcomes with higher temperature. In this study, we observed that some individual- and community-level characteristics may affect the associations between heat exposure and preterm birth, although the results were not statistically different. Our findings are consistent with previous literature showing that younger or older maternal age is associated with higher risk of heat on preterm birth (Basu et al., 2010; Schifano et al., 2013). A recent study in California suggested that several maternal characteristics may increase susceptibilities to preterm delivery associated with higher apparent temperature. They found higher risk for younger mothers (Basu et al., 2017). Younger maternal age may relate with lower socioeconomic status (e.g., less education, low income, and unmarried mother) (Cho et al., 2004; Holditch-Davis et al., 2007), although we adjusted for individual-level SES. Previous studies reported that the status of older mother is also associated with preterm birth (Carolan, 2013). Our findings showed slightly higher risk of heat for preterm birth for female infants or infants from mothers with lower maternal education, although results were not statistically different from other infants. A study investigating the association between high ambient temperature and risk of preterm delivery showed no significant differences by infant's sex or maternal education (Basu et al., 2010).

Although a growing body of literature suggests vulnerabilities to adverse birth outcomes with higher temperature by individual and maternal characteristics, there is still lack of evidence on potential effect modifiers on these associations and results are not consistent. Several factors such as social and environmental characteristics that can affect the associations between heat exposure and adverse birth outcomes may be correlated with each other. Moreover, a combination of those factors could play an important role. In this study, we used maternal education as a proxy for SES. This may not fully reflect true SES because actual socioeconomic status may relate with many other factors such as historical income, family income, living conditions, and air conditioning system at the residence. Moreover, vulnerabilities to temperature effect may differ by location and several population characteristics such as regional climate condition and age structure of the population. Thus, more studies in various locations in different climates and populations are needed to evaluate vulnerabilities to heat effects on adverse birth outcomes, and potential effect modification.

In this study, we examined whether the community-level characteristics such as community-level SES and residential greenness of mother's residential address affect the association between heat exposure during pregnancy and preterm birth. We found that lower community-level SES was associated with higher risk of heat exposure on preterm birth. However, we did not find significant difference of heat effect by residential greenness. In investigation of combined disparities by individual- and community-level SES, we found the highest and most significant estimated effect for those in both categories of lower SES level (i.e., infants with mothers who have low individual-level SES, as estimated by low educational attainment, and low community-level SES). We also found lower risk of heat exposure on preterm birth in infants with mother who have low individual-level SES but higher community-level SES. Our findings suggest that both individual- and community-level SES play a role in the association between heat and risk of preterm birth.

Very few studies have evaluated the effect modification of community-level factors for the association between heat exposure and birth outcomes. Thus, we report on previous literature of the association between community-level factors and adverse birth outcomes. Several previous studies reported that community-level factors, such as greenness of mother's residential area, population density, area-level SES, and other social or environmental factors, may contribute to risk of adverse birth outcomes (Agay-Shay et al., 2014; Farley et al., 2006; Kent et al., 2013). Higher surrounding greenness was associated with increased birth weight (Dadvand et al., 2012). Hystad et al. (2014) found that increased residential greenness was associated with higher birth weight at full term, lower likelihood of small for gestational age, very preterm (< 30 weeks), and moderately preterm (30–36 weeks) birth. However, Cusack et al. (2017) observed no significant associations between residential NDVI (Normalized Difference Vegetation Index) exposure and birth outcomes. Possible reasons for inconsistent findings may be the differences in ecological environment and region-specific characteristics (e.g., fairly similar NDVI levels across gus compared to other study areas). Future studies in different areas are needed to clarify the potential effect modification of community-level factors on the heat-related adverse birth outcomes.

A limitation to this study was the use of meteorological data from one monitoring site for all gus due to data availability. We could not consider individual heat exposure for each study participant or high-resolution meteorological data as such data were not available. However, we anticipate that potential bias from any exposure misclassification is non-differential. The use of data from monitoring stations that may not capture the spatial variability in temperature may induce bias, which underestimates the effect size. A previous study compared the association between temperature and mortality using high spatial resolution data (based on satellite imagery and other land use sources) and monitoring station data and found larger estimated effect sizes for heat using high-resolution temperature data compared to results based on the monitoring station data (Lee et al., 2016). Also, high spatial resolution of ambient temperature data within the city may not fully reflect the actual heat exposure for each study participants because actual heat exposure would relate with several factors such as time-activity patterns, amount of time spent indoors versus outdoors, and indoor temperature as well as use of adaptation measures (e.g., air conditioning). We could not account for some potential confounding

factors for the relationship between temperature and adverse birth outcomes such as maternal risk factors (e.g., smoking history, previous medical condition, prenatal care). However, we adjusted for variables such as maternal age and education level in our model, which may correlate with those factors, and further these variables for which data are not available may not be correlated with temperature. We could not identify multiple births during the study period for a particular mother as such information was not available. Thus, we could not consider clustering or co-linearity issues for correlated outcomes based on the same mother. A previous study examined individual-level risk of preterm delivery based on mother's exposure to $PM_{2.5}$ during pregnancy, comparing multiple pregnancies in the same woman rather than risks from between-women comparisons (Pereira et al., 2014). This comparison allows to unmeasured factors that vary across women to be less influential. In this study, we used logistic regression analysis to estimate the effect of temperature on adverse birth outcomes as commonly used in many previous studies (Zheng et al., 2018; Guo et al., 2018). Several studies confirmed that survival analysis is more effective than conventional approaches to account for time-dependent exposure and outcome (Platt et al., 2004; O'Neill et al., 2003). We also added new sensitivity analysis using extended Cox proportional hazard model, and found similar results with our original findings. Future studies could consider exposure data with more spatial variability, further information on potential confounding factors, or alternative statistical approaches.

In this study, we used information of residential address at birth. We could not consider residential mobility during pregnancy, which may introduce exposure misclassification. A previous review study of moves of women during pregnancy reported that most moves were short distances (< 10 km), thus exposures that are largely homogeneous within a community may not greatly affect the result (Bell and Belanger, 2012). Another study compared effect estimates of PM_{10} on fetal growth and gestational length, finding a negligible difference of effects with and without accounting for residential mobility (Pereira et al., 2016).

5. Conclusions

To our knowledge, this is the first study to investigate the associations between heat exposure based on multiple exposure windows and adverse birth outcomes for Korea. This is also the first study, to the best of our knowledge, to evaluate effect modification by several individual- and community-level characteristics in heat-related adverse outcomes for Korea. Our study is based in a different area and time frame than other studies and thereby adds evidence to the relatively limited and inconsistent body of literature regarding the association between heat exposure and adverse birth outcomes. Our findings provide evidence that heat exposure during whole pregnancy, 4 weeks before delivery, and 1 week before delivery are associated with increased risk of preterm birth in Seoul, Korea. Higher risk of heat on preterm birth was associated with some individual characteristics such as maternal age and community-level SES. Our findings have implications for future studies evaluating impacts of high temperatures on adverse birth outcomes and identifying which subpopulations and factors are most relevant for disparities in this association. More research in other locations including study of potential individual- and community-level effect modification of how heat affects adverse birth outcomes should be conducted to reduce the burden of adverse birth outcomes. Such work is particularly relevant due to the anticipated increase in overall high temperature and extreme temperatures under climate change.

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Declarations of interest

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envres.2018.10.032.

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